

# An Observational Test for the Anthropic Origin of the Cosmological Constant

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The existence of multiple regions of space beyond the observable Universe (within the so-called *multiverse*) where the vacuum energy density takes different values, has been postulated as an explanation for the low non-zero value observed for it in our Universe. It is often argued that our existence pre-selects regions where the cosmological constant is sufficiently small to allow galaxies like the Milky Way to form and intelligent life to emerge. At first glance, it would seem necessary to visit regions of space far beyond our current horizon in order to critically examine the validity of this *anthropic* argument. However, here we propose a simple empirical test for it within the boundaries of the observable Universe. We make use of the fact that dwarf galaxies formed in our Universe at redshifts as high as  $z \sim 10$  when the mean matter density was larger by a factor of  $\sim 10^3$  than today. Existing technology enables to check whether planets form in nearby dwarf galaxies and globular clusters by searching for microlensing or transit events of background stars. The oldest of these nearby systems may have formed at  $z \sim 10$ . Direct observations of dwarf galaxies at redshifts  $z \sim 10$  can be used to characterize their size, mass, metallicity, and star formation history, and identify the nearby systems that descended from them. If planets are as common per stellar mass in these descendants as they are in the Milky Way galaxy, then the anthropic argument would be weakened considerably since planets could have formed in our Universe even if the cosmological constant,  $\rho_V$ , was three orders of magnitude larger than observed. For a flat probability distribution at the relevant  $\rho_V$  values (which represent infinitesimal deviations from zero in Planck units), this would imply that the probability for us to reside in a region where  $\rho_V$  obtains its observed value is lower than  $\sim 10^{-3}$ . A precise version of the anthropic argument could then be ruled-out at a confidence level of  $\sim 99.9\%$  which constitutes a satisfactory measure of a good experimental test.

## I. INTRODUCTION

The distance to Type Ia supernovae [1, 2] and the statistics of the cosmic microwave background anisotropies [3] provide conclusive evidence for a finite vacuum energy density of  $\rho_V = 4 \text{ keV cm}^{-3}$  in the present-day Universe. This value is almost three times larger than the mean cosmic density of matter today. The expected exponential expansion of the Universe in the future (for a time-independent vacuum density) will halt the growth of all bound systems such as galaxies and groups of galaxies [4, 5, 6]. It will also redshift all extragalactic sources out of detectability (except for the merger remnant of the Milky Way and the Andromeda galaxies to which we are bound) – marking the end of extragalactic astronomy, as soon as the Universe will age by another factor of ten [7].

The observed vacuum density is smaller by tens of orders of magnitude than any plausible zero-point scale of the Standard Model of particle physics. Weinberg [8] and Linde [9] first suggested that such a situation could arise in a theory that allows the cosmological constant to be a free parameter. On a scale much bigger than the observable Universe one could then find regions in which the value of  $\rho_V$  is very different. However, if one selects those regions that give life to observers, then one would find a rather limited range of  $\rho_V$  values near its observed magnitude, since observers are most likely to appear in galaxies as massive as the Milky-way galaxy which assembled at the last moment before the cosmological constant started to dominate our Universe. Vilenkin [10] showed that this

so-called “anthropic argument” [11] can be used to calculate the probability distribution of vacuum densities with testable predictions. This notion [12, 13, 14, 15, 16, 17] gained popularity when it was realized that string theory predicts the existence of an extremely large number [18, 19, 20, 21], perhaps as large as  $\sim 10^{100}$  to  $10^{500}$  [22], of possible vacuum states. The resulting landscape of string vacua [23] in the “multiverse” encompassing a volume of space far greater than our own inflationary patch, made the anthropic argument appealing to particle physicists and cosmologists alike [17, 24, 25].

The time is therefore ripe to examine the prospects for an experimental test of the anthropic argument. Any such test should be welcomed by proponents of the anthropic argument, since it would elevate the idea to the status of a falsifiable physical theory. At the same time, the test should also be welcomed by opponents of anthropic reasoning, since such a test would provide an opportunity to diminish the predictive power of the anthropic proposal and suppress discussions about it in the scientific literature.

*Is it possible to dispute the anthropic argument without visiting regions of space that extend far beyond the inflationary patch of our observable Universe?* The answer is *yes* if one can demonstrate that life could have emerged in our Universe even if the cosmological constant would have had values that are much larger than observed. In §III and §IV we propose a set of astronomical observations that could critically examine this issue. We make use of the fact that dwarf galaxies formed in our Universe at redshifts as high as  $z \sim 10$  when the mean matter den-

sity was larger by a factor of  $\sim 10^3$  than it is today [98] [26]. If habitable planets emerged within these dwarf galaxies or their descendents (such as old globular clusters which might be the tidally truncated relics of early galaxies [27, 28]), then life would have been possible in a Universe with a value of  $\rho_V$  that is a thousand times bigger than observed.

## II. PRIOR PROBABILITY DISTRIBUTION OF VACUUM DENSITIES

On the Planck scale of a quantum field theory which is unified with gravity (such as string theory), the vacuum energy densities under discussion represent extremely small deviations around  $\rho_V = 0$ . Assuming that the prior probability distribution of vacuum densities,  $\mathcal{P}_*(\rho_V)$ , is not divergent at  $\rho_V = 0$  (since  $\rho_V = 0$  is not favored by any existing theory), it is natural to expand it in a Taylor series and keep only the leading term. Thus, in our range of interest of  $\rho_V$  values [15, 16],

$$\mathcal{P}_*(\rho_V) \approx \text{const.} \quad (1)$$

This implies that the probability of measuring a value equal to or smaller than the observed value of  $\rho_V$  is  $\sim 10^{-3}$  if habitable planets could have formed in a Universe with a value of  $\rho_V$  that is a thousand times bigger than observed.

Numerical simulations indicate that our Universe would cease to make new bound systems in the near future [4, 5, 6]. A Universe in which  $\rho_V$  is a thousand times larger, would therefore make dwarf galaxies until  $z \sim 10$  when the matter density was a thousand times larger than today. The question of whether planets can form within these dwarf galaxies can be examined observationally as we discuss next. It is important to note that once a dwarf galaxy forms, it has an arbitrarily long time to convert its gas into stars and planets, since its internal evolution is decoupled from the global expansion of the Universe (as long as outflows do not carry material out of its gravitational pull).

## III. EXTRAGALACTIC PLANET SEARCHES

Gravitational microlensing is the most effective search method for planets beyond our galaxy. The planet introduces a short-term distortion to the otherwise smooth lightcurve produced by its parent star as that star focuses the light from a background star which happens to lie behind it [29]–[43]. In an extensive search for planetary microlensing signatures, a number of collaborations named PLANET [44],  $\mu$ FUN [45] and RoboNET [46], are performing follow-up observations on microlensing events which are routinely detected by the groups MOA [47] and OGLE [48]. Four “planetary” events have been reported

so far (see Ref. [49] for a summary), including a planet of a mass of  $\sim 5$  Earth masses at a projected separation of 2.6 AU from a  $0.2 M_\odot$  M-dwarf star in the microlensing event OGLE-2005-BLG-390Lb [50], and a planet of 13 Earth masses at a projected separation of 2.3 AU from its parent star in the event OGLE-2005-BLG-169 towards the Galactic bulge – in which the background star was magnified by the unusually high factor of  $\sim 800$  [52]. Based on the statistics of these events and the search parameters, one can infer strong conclusions about the abundance of planets of various masses and orbital separations in the surveyed star population [51, 52, 53]. The technique can be easily extended to lenses outside our galaxy and out to the Andromeda galaxy (M31) using the method of pixel lensing [54, 55, 56]. For the anthropic experiment, we are particularly interested in applying this search technique to lensing of background Milky-Way stars by old stars in foreground globular clusters (which may be the tidally-truncated relics of  $z \sim 10$  galaxies), or to lensing of background M31 stars by foreground globular clusters [57] or dwarf galaxies such as Andromeda VIII [58]. In addition, self-lensing events in which foreground stars of a dwarf galaxy lens background stars of the same galaxy, are of particular interest. Such self-lensing events were observed in the form of caustic-crossing binary lens events in the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) [59]. In the observed cases there is enough information to ascertain that the most likely lens location is in the Magellanic Clouds themselves. Yet, each caustic-crossing event represents a much larger number of binary lens events from the same lens population; the majority of these may be indistinguishable from point-lens events. It is therefore possible that some of the known single-star LMC lensing events are due to self-lensing [59], as hinted by their geometric distribution [60, 61].

Another method for finding extra-Galactic planets involves transit events in which the planet passes in front of its parent star and causes a slight temporary dimming of the star. Spectral modeling of the parent star allows to constrain both the size and abundance statistics of the transiting planets [62, 63]. Existing surveys reach distance scales of several kpc [65]–[69] with some successful detections [70, 71, 72]. So far, a Hubble Space Telescope search for transiting Jupiters in the globular cluster 47 Tucanae resulted in no detections [74] [although a pulsar planet was discovered later by a different technique in the low-metallicity globular cluster Messier 4 [73], potentially indicating early planet formation]. A future space telescope (beyond the planned Kepler [99] and COROT [100] missions which focus on nearby stars) or a large-aperture ground-based facility (such as the Giant Magellan Telescope [GMT][101], the Thirty-Meter Telescope [TMT][102], or the Overwhelmingly Large Telescope [OWL][103]) could extend the transit search technique to planets at yet larger distances (but see Ref.

[63]). Recent searches [62] identified the need for a high signal-to-noise spectroscopy as a follow-up technique for confirming real transits out of many false events. Such follow-ups would become more challenging at large distances, making the microlensing technique more practical.

#### IV. OBSERVATIONS OF DWARF GALAXIES AT HIGH-REDSHIFTS

Our goal is to study stellar systems in the local Universe which are the likely descendents of the early population of  $z \sim 10$  galaxies [75]. In order to refine this selection, it would be desirable to measure the characteristic size, mass, metallicity, and star formation histories of  $z \sim 10$  galaxies (see Ref. [26] for a review on their theoretically-expected properties). As already mentioned, it is possible that the oldest globular clusters are descendents of the first galaxies [76, 77].

Recently, a large number of faint early galaxies, born less than a billion years after the big bang, have been discovered [78]–[87]. These include starburst galaxies with star formation rates in excess of  $\sim 0.1 M_\odot \text{ yr}^{-1}$  and dark matter halos [82] of  $\sim 10^9\text{--}11 M_\odot$  [78, 81, 83, 84, 85] at  $z \sim 5\text{--}10$ . Luminous Ly $\alpha$  emitters are routinely identified through continuum dropout and narrow band imaging techniques [79, 81, 88]. In order to study fainter sources which were potentially responsible for reionization, spectroscopic searches have been undertaken near the critical curves of lensing galaxy clusters [84, 85, 87], where gravitational magnification enhances the flux sensitivity. Because of the foreground emission and opacity of the Earth's atmosphere, it is difficult to measure spectral features other than the Ly $\alpha$  emission line from these feeble galaxies from ground-based telescopes.

In one example, gravitational lensing by the massive galaxy cluster A2218 allowed to detect a stellar system at  $z = 5.6$  with an estimated mass of  $\sim 10^6 M_\odot$  in stars [84]. Detection of additional low mass systems could potentially reveal whether globular clusters formed at these high redshifts. Such a detection would be feasible with the *James Webb Space Telescope* (<http://www.jwst.nasa.gov/>). Existing designs for future large-aperture ( $> 20\text{m}$ ) infrared telescopes (such as the GMT, TMT, and OWL mentioned above), would also enable to measure the spectra of galaxies at  $z \sim 10$  and infer their properties.

Based the characteristics of high- $z$  galaxies, one would be able to identify present-day systems (such as dwarf galaxies or globular clusters) that are their likely descendents [89, 90] and search for planets within them. Since the lifetime of massive stars that explode as core-collapse supernovae is two orders of magnitude shorter than the age of the universe at  $z \sim 10$ , it is possible that some of these systems would be enriched to a high metallicity de-

spite their old age. For example, the cores of quasar host galaxies are known to possess super-solar metallicities at  $z \gtrsim 6$  [91].

#### V. DISCUSSION

Over the next decade, it would be technologically feasible to search for microlensing or transit events in local dwarf galaxies or old globular clusters and to check whether planets exist in these environments. Complementary observations of early dwarf galaxies at redshifts  $z \sim 10$  can be used to identify nearby galaxies or globular clusters that are their likely descendents. If planets are found in local galaxies that resemble their counterparts at  $z \sim 10$ , then the precise version of the anthropic argument [8, 10, 12, 13, 16] would be weakened considerably, since planets could have formed in our Universe even if the cosmological constant,  $\rho_V$ , was three orders of magnitude larger. For a flat probability distribution at these  $\rho_V$  values (which represents infinitesimal deviations from  $\rho_V = 0$  relative to the Planck scale), this would imply that the probability for us to reside in a region where  $\rho_V$  obtains its observed value is lower than  $\sim 10^{-3}$ . The precise version of the anthropic argument [8, 10, 12, 13, 16] could then be ruled-out at a confidence level of  $\sim 99.9\%$ , which is a satisfactory measure for an experimental test. The envisioned experiment resonates with two of the most active frontiers in astrophysics, namely the search for planets and the study of high-redshift galaxies, and if performed it would have many side benefits to conventional astrophysics.

We note that in the hypothetical Universe with a large cosmological constant, life need not form at  $z \sim 10$  (merely 400 million years after the big bang) but rather any time later. Billions of years after a dwarf galaxy had formed – a typical astronomer within it would see the host galaxy surrounded by a void which is dominated by the cosmological constant.

An additional factor that enters the likelihood function of  $\rho_V$  values involves the conversion efficiency of baryons into observers in the Universe. A Universe in which observers only reside in galaxies that were made at  $z \sim 10$  might be less effective at making observers. The fraction of baryons that have assembled into star-forming galaxies above the hydrogen cooling threshold by  $z \sim 10$  is estimated to be  $\sim 10\%$  (see Fig. 13 in Ref. [26]), comparable to the final fraction of baryons that condensed into stars in the present-day Universe [92]. It is possible that more stars formed in smaller systems down to the Jeans mass of  $\sim 10^{4\text{--}5} M_\odot$  through molecular hydrogen cooling [93]. Although today most baryons reside in a warm-hot medium of  $\sim 2 \times 10^6 \text{K}$  that cannot condense into stars [94, 95], most of the cosmic gas at  $z \sim 10$  was sufficiently cold to fragment into stars as long as it could have cooled below the virial temperature of its host ha-

los [26]. The star formation efficiency can be inferred [89] from dynamical measurements of the star and dark matter masses in local dwarfs or globulars that resemble their counterparts at  $z \sim 10$ . If only a small portion of the cosmic baryon fraction ( $\Omega_b/\Omega_m$ ) in dwarf galaxies is converted into stars, then the probability of obtaining habitable planets would be reduced accordingly. Other physical factors, such as metallicity, may also play an important role. Preliminary evidence indicates that planet formation favors environments which are abundant in heavy elements [96], although notable exceptions exist [73].

Unfortunately, it is not possible to infer the planet production efficiency for an alternative Universe purely based on observations of our Universe. In our Universe, most of the baryons which were assembled into galaxies by  $z \sim 10$  are later incorporated into bigger galaxies. The vast majority of the  $z \sim 10$  galaxies are consumed through hierarchical mergers to make bigger galaxies; isolated descendents of  $z \sim 10$  galaxies are rare among low-redshift galaxies. At any given redshift below 10, it would be difficult to separate observationally the level of planet formation in our Universe from the level that would have occurred otherwise in smaller galaxies if these were not consumed by bigger galaxies within a Universe with a large vacuum density,  $\rho_V$ . In order to figure out the planet production efficiency for a large  $\rho_V$ , one must adopt a strategy that mixes observations with theory. Suppose we observe today the planet production efficiency in the descendents of  $z \sim 10$  galaxies. One could then use numerical simulations to calculate the abundance that these galaxies would have had today if  $\rho_V$  was  $\sim 10^3$  times bigger than its observed value. This approach takes implicitly into account the possibility that planets may form relatively late (after  $\sim 10$  Gyr) within these isolated descendents, irrespective of the value of  $\rho_V$ . The late time properties of gravitationally-bound systems are expected to be independent of the value of  $\rho_V$ .

In our discussion, we assumed that as long as rocky planets can form at orbital radii that allow liquid water to exist on their surface (the so-called *habitable zone* [97]), life would develop over billions of years and eventually mature in intelligence. Without a better understanding of the origin of intelligent life, it is difficult to assess the physical conditions that are required for intelligence to emerge beyond the minimal requirements stated above. If life forms early then civilizations might have more time to evolve to advanced levels. On the other hand, life may be disrupted more easily in early galaxies because of their higher density (making the likelihood of stellar encounters higher) [14, 16], and so it would be useful to determine the environmental density observationally. In the more distant future, it might be possible to supplement the study proposed here by the more adventurous search for radio signals from intelligent civilizations be-

yond the boundaries of our galaxy. Such a search would bring an extra benefit. If the anthropic argument turns out to be wrong and intelligent civilizations are common in nearby dwarf galaxies, then the older more advanced civilizations among them might broadcast an explanation for why the cosmological constant has its observed value.

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Milky-Way galaxy formed before  $\rho_V$  dominated but it could have also formed later.

[99] <http://kepler.nasa.gov/>

[100] <http://smc.cnes.fr/COROT/>

[101] <http://www.gmto.org/>

[102] <http://www.astro.caltech.edu/observatories/tmt/>

[103] <http://www.eso.org/projects/owl/>